

The LMT* Galaxies' 3 mm Spectroscopic Survey: First Results

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Abstract The molecular phase of the interstellar medium (ISM) in galaxies offers fundamental insight for understanding star-formation processes and how stellar feedback affects the nuclear activity of certain galaxies. We present here Large Millimeter Telescope spectra obtained with the Redshift Search Receiver, a spectrograph that covers simultaneously the 3 mm band from 74 to 111 GHz with a spectral resolution of around 100 km s^{-1} . Our selected galaxies, have been detected previously in HCN, and have different degrees of nuclear activity — one normal galaxy (NGC 6946), the starburst prototype (M 82) and two ultraluminous infrared galaxies (ULIRGs, IRAS 17208-0014 and Mrk 231). We plotted our data in the HCO^+/HCN vs. $\text{HCN}/^{13}\text{CO}$ diagnostic diagram finding that NGC 6946 and M 82 are located close to other normal galaxies; and that both IRAS 17208-0014 and Mrk 231 are close to the position of the well known ULIRG Arp 220 reported by Snell et al. (2011). We found that in Mrk 231 – a galaxy with a well known active galactic nucleus – the HCO^+/HCN ratio is similar to the ratio observed in other normal galaxies.

1 Introduction

The starburst– active galactic nucleus (AGN) connection is one of the most interesting and evolving topics of modern astronomy. Learning about nuclear activity in galaxies implies segregating the different components present in the nuclei of galaxies, plus allowing for a range of ages, metal content and environmental differences. For example, when dealing with AGNs and nuclear starbursts (SBs) one has to take into account that AGNs tend to appear preferentially in early type galaxies while SBs tend to appear in Hubble types later than Sbc. This implies that – on

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average – physical parameters like metallicity or the age of the underlying stellar population are different in AGNs and SBs. In general, Seyfert galaxies have metal content higher than the SB galaxies, thus the properties of the star formation in SB nuclei are not necessarily similar to the star formation in Seyfert nuclei. Part of the problem is that galactic nuclei, where these processes take place, can be very dusty. This compromises the interpretation of short-wavelength observations, and makes a multi-wavelength approach imperative. One possible solution is to take advantage of sub-millimeter and millimeter (mm) spectra, only recently possible thanks to new facilities. The mm-wavelength spectral surveys are beginning to provide sensitive measurements of an astounding number of molecular transitions in starbursts and AGNs (e.g. García Burillo et al., 2010; Aladro et al., 2011, 2013). Such transitions allow the detailed study of molecular chemistry in galactic nuclei, interpreted through theoretical models only now starting to achieve the necessary sophistication (e.g. Papadopoulos, 2010; Kazandjian et al., 2012; Bayet et al., 2012). The mm spectral line ratios provide diagnostics to interpret the relative contributions of different physical environments in and around molecular clouds in the nuclear regions of galaxies. Depending on the strengths of AGN accretion and star formation, molecular chemistry can be driven by Photo-Dissociated Regions (PDRs), Cosmic-Ray Dominated Regions (CRDRs), X-ray Dominated Regions (XDRs), shock-dominated regions (or mechanically heated regions), and dense shielded regions which lie deep in the molecular cloud ensembles. One of the main parameters that drives the evolution of a given galaxy is the star formation rate (SFR) which is related to the presence of dense shielded cores with $n(\text{H}_2) > 3 \times 10^4 \text{ cm}^{-3}$. These regions are traced by molecules with high dipole moment such as HCN and CS. In fact the HCN luminosity in CO bright galaxies seems to correlate very well with the infrared luminosity, a common tracer of the star formation activity (Gao & Solomon, 2004a,b). Lines in the 3mm spectral region such as CO, HCN, HNC, HCO^+ , and CS have been used (e.g. Kohn et al., 2001; Gracia Carpio et al., 2006; Snell et al., 2011) to reveal and separate PDRs and CRDRs, associated with SF and intense starbursts, from XDRs, typically associated with AGNs (e.g. Papadopoulos, 2010; Meijerink et al., 2011). It is interesting to see that the old problem of determining the source of energy in the nucleus of nearby galaxies – star formation or accretion to black holes – is still present in recent studies of molecular chemistry. Rare isotopes such as C^{18}O and ^{13}CO may trace rapid ISM enrichment and in some cases they have been related to the presence of WR stars or Type II SNe (e.g., Costagliola et al. 2011).

2 Observations and Data Reduction

The Redshift Search Receiver (RSR) is a dual polarization and dual beam instrument. The four broadband receivers cover instantaneously the frequency range 74 – 111 GHz implying a very good relative calibration of the observed lines and making this instrument unique. Spectra are obtained by alternately positioning the source in

one of the two beams of the receiver. In this way, the source is always being observed. Observations are made for 30 seconds in each beam and the spectra are then subtracted from one another to obtain the spectrum of the difference between source and sky. Calibration is done by the traditional chopper wheel method wherein a measurement of an ambient load and sky are used to derive the system temperature and the antenna temperature of sources according to the TA^* scale. Typical values of the system temperature were around 100K. Observations were always made by first peaking up the pointing and focus of the antenna on a nearby radio source, having a pointing accuracy of $1''$ – $2''$ for the $\sim 25''$ beam of the LMT at 3mm wavelength. We make use of the data analysis package called **Dreampy** (Data Reduction and Analysis Methods in Python), written by G. Narayanan for reducing the data from the RSR. After converting and calibrating the raw data and combining the frequency bands, the data in four pixels were averaged together using available routines in **Dreampy** to produce final spectra for each galaxy.

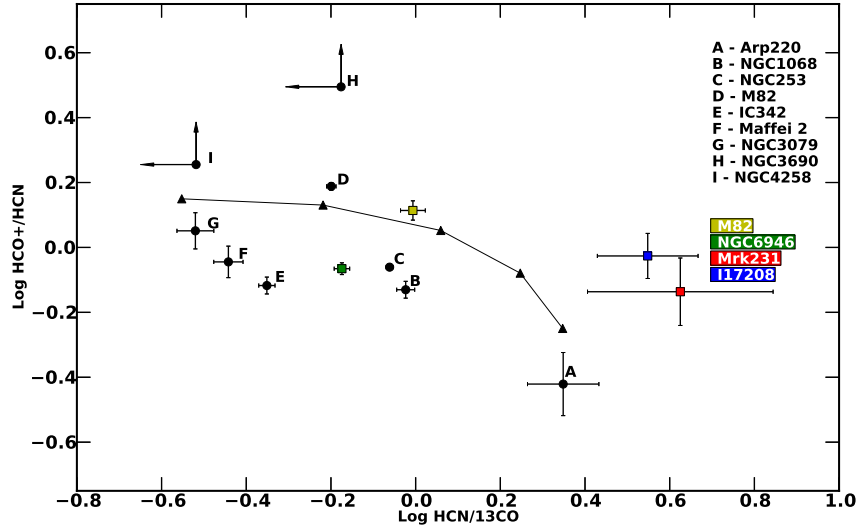


Fig. 1 The observed line ratios compared with different theoretical models. As an example, we show the comparison carried out by Snell et al. (2011) in a sample of galaxies observed with the RSR mounted on the FCRAO telescope (black circles). The emission line ratios were modeled using the RADEX code (van der Tak et al., 2007). The output of the models are marked with filled triangles connected by the solid line. From the left to the right, the log-density of the different models are $n(H_2)=4.0, 4.5, 5.0, 5.5$ and 6.0 cm^{-3} . A temperature of 35 K was fixed for all the models. In colored squares we mark the position of the galaxies observed by our team.

3 Results and Conclusions

The observations discussed in this paper include M 82 which was observed with the RSR at the LMT during the first-light scientific demonstration observations phase in June 2011, and NGC 6946, IRAS 17208-0014 and Mrk 231 that were observed during the summer of 2013. In the observed 3 mm spectra of these galaxies we detected several lines including, in some cases, lines as weak as CN which traces very dense molecular gas ($n(\text{H}_2) \sim 10^6 \text{ cm}^{-3}$). However, we are reporting only our results on the HCN, HCO^+ and ^{13}CO lines. In Fig. 1 we plotted our results in the HCO^+/HCN vs. $\text{HCN}/^{13}\text{CO}$ diagnostic diagram. In that diagram the horizontal axis is an indicative of the dense gas fraction, where galaxies with high fraction of dense gas, $N(\text{H}_2) \sim 10^5 \text{ cm}^{-3}$, are located to the right, and the vertical one is related with the presence of an AGN where those galaxies with HCO^+/HCN much greater than 1 are better explained by models that include X-ray dominated regions (e.g. Meijerink et al., 2011). M 82 and NGC 6946 are close to other normal galaxies reported by Snell et al. (2011). In that paper they also observed M 82 (marked with a D in the Figure) with the same receiver but mounted in the FCRAO 15 m antenna. The differences between the HCN, ^{13}CO ratio can be explained by the different beam sizes between the LMT and the FCRAO and the relative distribution of the dense gas traced by HCN and the more diffuse gas traced by ^{13}CO . The two ultra-luminous galaxies (ULIRGs) observed, IRAS 17208-0014 and Mrk 231, are close to the position of the well known ULIRG Arp 220, indicating the presence of high amounts of dense gas in both galaxies. Notice that Mrk 231, a well known active galaxy classified as a Seyfert 1, has not an HCO^+ enhancement as predicted by the theoretical models. By using all the available data of this galaxy, which cover all the electromagnetic spectrum, we expect to better understand this discrepancy.

We are witnessing the capability of the RSR–LMT system through the first results of an ongoing project where we will observe hundreds of galaxies with different degree of central activity – from HII galaxies, starbursts, LINERS, Seyfert 1–2, and luminosities – from normal galaxies to luminous and ultra luminous infrared galaxies, and we will be able to relate with high statistical significance the properties of nuclear activity with the complex molecular chemistry.

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